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Original scientific paper

Transmission Power System Planning Under New Generation Insecurity

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Abstract: The integration of renewable energy sources into the power grid presents significant challenges and opportunities for grid planners. Renewable energy sources such as wind and solar are variable and intermittent, leading to fluctuations in power output based on weather conditions and time of day. This variability necessitates the development of more flexible and responsive systems to balance supply and demand effectively. Traditional power plants, which provide consistent and controllable power, have long been the backbone of grid stability. However, the increasing penetration of renewables introduces complexities such as voltage instability and frequency fluctuations. To address these issues, grid planners must implement advanced technologies and strategies, including energy storage systems and smart grid technologies, to maintain stability and reliability. The transition to renewable energy also requires substantial upgrades to the existing grid infrastructure. This includes expanding transmission lines to connect remote renewable energy sites to the main grid and enhancing distribution networks to handle the increased load and variability. The shift towards a more decentralized energy system, where power generation occurs closer to consumption points, challenges traditional centralized grid models. Grid planners must now incorporate distributed energy resources (DERs) like rooftop solar panels and local wind turbines into their planning processes. By addressing these challenges, grid planners can create a more sustainable, reliable, and resilient energy system that effectively integrates renewable energy sources.

Keywords: contingency, DC load flow, electricity network, sensitivity analysis, test network, transmission system planning

1 INTRODUCTION

Renewable energy sources significantly impact grid planning in several ways. Renewable energy sources like wind and solar are variable and intermittent, meaning their power output can fluctuate based on weather conditions and time of day. This variability requires grid planners to incorporate more flexible and responsive systems to balance supply and demand [1-3]. Traditional power plants provide consistent and controllable power, which helps maintain grid stability. In contrast, renewables can introduce challenges such as voltage instability and frequency fluctuations. Grid planners must implement advanced technologies and strategies, such as energy storage systems and smart grid technologies, to ensure stability and reliability.

Integrating renewables often necessitates significant upgrades to the existing grid infrastructure. This includes expanding transmission lines to connect remote renewable energy sites to the main grid and enhancing distribution networks to handle the increased load and variability. Renewables promote a more decentralized energy system, with power generation occurring closer to where it is consumed. This shift requires grid planners to rethink traditional centralized grid models and incorporate distributed energy resources (DERs) like rooftop solar panels and local wind turbines.

The transition to renewable energy requires substantial investment in new technologies and infrastructure. Grid planners must also navigate evolving policies and regulations aimed at promoting renewable energy adoption and ensuring grid resilience. As climate change increases the frequency and severity of extreme weather events, grid planners must design systems that are resilient to these impacts. This includes hardening infrastructure against storms and heatwaves and incorporating climate risk assessments into planning processes.

By addressing these challenges, grid planners can create a more sustainable, reliable, and resilient energy system that effectively integrates renewable energy sources.

Electric power systems (EPS) were originally constructed decades ago, tailored for electricity generation from conventional energy sources. The process of developing and constructing these traditional power plants is extensive, often exceeding 10 years. However, with the rise of new energy sources, particularly wind and solar, this timeline has been significantly reduced to 4 - 5 years.

In this evolving landscape, the development of the necessary electricity infrastructure has not kept pace, necessitating the optimization of the electricity network's development. This ensures that new power plants can connect seamlessly without compromising system safety and reliability.

While no two EPS are identical, they all share the fundamental requirement that generation must match consumption (including losses). Planning the development and upgrade of a transmission system is becoming increasingly challenging, especially when there are no guarantees that all proposed power plants will ultimately be built and connected to the network.

The deterministic approach involves planning based on fixed inputs and assumptions, assuming that all parameters (such as demand, generation capacity, and system conditions) are known and constant over the planning horizon. This method is straightforward and easier to implement but may not account for real-world uncertainties and variations.

The stochastic approach, in contrast, incorporates uncertainties and variations into the planning process. It uses probabilistic models to account for variability in parameters like demand, generation from renewable sources, and system outages. This approach is more complex but offers a more robust and flexible plan that can adapt to different scenarios.

Optimization techniques are crucial in both approaches to find the best possible solutions under given constraints. Commonly used techniques include:

Stochastic Programming (SP) is used in the stochastic approach to model uncertainties explicitly, involving multiple scenarios to find optimal solutions.

Robust Optimization (RO) aims to find solutions feasible under worst-case scenarios, particularly useful for dealing with uncertainties in the stochastic approach.

Mixed-Integer Linear Programming (MILP) is often used in deterministic models to handle discrete decisions, such as constructing new transmission lines.

Distributionally Robust Optimization (DRO) is a novel approach combining elements of both SP and RO, aiming to provide solutions robust against a range of probability distributions of uncertain parameters.

By integrating these optimization techniques, planners can develop more efficient and resilient electricity transmission systems capable of handling the uncertainties and complexities of modern power grids.

In literature, there are papers that present an improvement to the algorithm for calculating power flows in radial distribution systems using the breadth-first search method to create a modified incidence matrix. The traditional backward/forward sweep (BFS) method uses an iterative approach to calculate power flows but can be slow due to the large number of searches between nodes. The improvement proposed in this paper uses breadth-first search to create a modified incidence matrix, reducing the number of required searches and speeding up the algorithm without losing accuracy. This approach is particularly useful for real-time calculations in active distribution system management, where calculation speed is crucial [22].

Some papers analyzed non-traditional optimization methods for the allocation of distributed generation and energy storage in the distribution system. Traditional optimization methods often fail to solve the complex problems of modern distribution networks, so this paper explores alternative methods such as genetic algorithms, particle swarm optimization, evolutionary algorithms, and other advanced techniques. These methods enable better resource utilization, increase network efficiency and reliability, and reduce operational costs. The review includes an analysis of the advantages and disadvantages of each method, as well as examples of their application in real distribution systems [23].

The increased implementation of renewable energy sources creates challenges in voltage regulation, system stability, and protection coordination. Traditional protection systems often cannot adequately respond to these challenges due to increased fault currents, invisibility of certain faults, and reduced range of protective devices. The proposed system uses automation to improve the management and protection of the distribution system, including real-time event analysis and adjustment of protection settings according to current network conditions. This approach enables better protection coordination and increases system reliability [25].

2 GRID DEVELOPMENT PLANNING

The development of electricity transmission networks involves several key stages. Planning and Design is an initial phase, includes assessing future energy demands, identifying potential generation sources, and designing the network layout. Strategic spatial planning and regulatory approvals are crucial at this stage. Obtaining the necessary permits and approvals from regulatory bodies is essential. This process can be lengthy and involves environmental assessments, public consultations, and compliance with local and national regulations [1].

Once approvals are in place, the construction phase begins. This includes building transmission lines, substations, and other infrastructure. The construction phase can take several years, depending on the project's complexity. After construction, the new infrastructure is integrated into the existing grid. This phase involves extensive testing to ensure the system operates reliably and safely. Once operational, the network requires ongoing maintenance and upgrades to ensure continued reliability and efficiency.

There are also many challenges and obstacles. Mainly:

- Regulatory Hurdles: Navigating the complex regulatory landscape can be time-consuming and costly. Delays in obtaining permits can significantly impact project timelines [4].
- Funding and Investment: Securing adequate funding for large-scale transmission projects is a major challenge. High upfront costs and long payback periods can deter investors [4].
- Technological Integration: Integrating new technologies, such as renewable energy sources and smart grid technologies, into existing networks can be complex and requires significant upgrades [4].
- Environmental and Social Impact: Transmission projects can face opposition due to their environmental and social impacts. Addressing these concerns through careful planning and community engagement is essential [1].
- Supply Chain and Skills Shortages: Ensuring a robust supply chain and skilled workforce is critical for timely project completion. Shortages in these areas can lead to delays and increased costs [1].

The European Network of Transmission System Operators for Electricity (ENTSO-E) and European Union Agency for the Cooperation of Energy Regulators (ACER) play a key role in developing European practices. European countries emphasize strategic planning and coordination to ensure efficient grid development. The EU has established comprehensive regulatory frameworks to facilitate cross-border electricity flows and ensure grid reliability. These frameworks include network codes and guidelines that standardize practices across member states [5]. Europe is investing heavily in innovative technologies to enhance grid efficiency and resilience. This includes the development of smart grids, energy storage solutions, and digitalization strategies [6].

Many European countries leverage public-private partnerships to fund and develop transmission projects. These partnerships help share risks and attract private investment [7]. European grid development practices prioritize sustainability and decarbonization. This includes integrating renewable energy sources, reducing carbon emissions, and enhancing grid flexibility to accommodate variable renewable generation [8].

By addressing these challenges and adopting best practices, Europe aims to develop a robust and resilient electricity transmission network that supports its energy transition goals.

3 MULTI-SCENARIO MODELING METHOD BASED ON DC POWER FLOW (METHODOLOGY FOR GRID DEVELOPMENT PLANNING)

To solve the problem of network development planning under uncertainties a multi-scenario modeling method based on the DC power flow was developed. The DC power flow model is very often used due to the large number of unknowns in the network development planning phase. More information on this topic can be found in [9-11].

This model is obtained by introducing the following assumptions:

- voltage magnitudes of all buses are 1 p.u.,
- voltage angle differences, for example between buses i and j are small and therefore is: $sin\left(\delta_{ij}\right) \approx \delta_{ij}$,
- line resistance is negligible, i.e. there are no losses of active power in the system,
- transformer tap settings are ignored.

Respecting these assumptions, for active and reactive power injected in the bus i, the following expressions are obtained:

$$P_i = \left|Y_{ii}\right| \times \cos\left(90°\right) + \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right| \times \sin\left(\delta_i - \delta_j\right) = \\ = \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right| \times \sin\left(\delta_i - \delta_j\right) \tag{1}$$

$$Q_i = \left|Y_{ii}\right| \times \sin\left(90°\right) - \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right| \times \cos\left(\delta_i - \delta_j\right) = \\ = \left|Y_{ii}\right| - \sum_{\substack{j=1 \\ j\neq i}}^{n} \left|Y_{ij}\right| \times \cos\left(\delta_i - \delta_j\right) \approx 0 \tag{2}$$

where:
Y_{ii} is a diagonal element of bus admittance matrix Y, Y_{ij} is a non-diagonal element of bus admittance matrix Y, n is the total number of buses in the network.

Introducing that $\left|Y_{ij}\right| = -B_{ij}$ (B_{ij} always has a negative value) and that for small angles is valid $sin\,\delta \approx \delta$, for the previously mentioned expressions is obtained:

$$P_i \approx -\sum_{\substack{j=1 \\ j\neq i}}^{n} B_{ij} \times \left(\delta_i - \delta_j\right) = -\delta_i \sum_{\substack{j=1 \\ j\neq i}}^{n} B_{ij} + \sum_{\substack{j=1 \\ j\neq i}}^{n} B_{ij} \times \delta_j = \\ = \delta_i \times B_{ii} + \sum_{\substack{j=1 \\ j\neq i}}^{n} B_{ij} \times \delta_j = \sum_{\substack{j=1 \\ j\neq i}}^{n} B_{ij} \times \delta_j \tag{3}$$

If n is a reference node for which is valid $\delta_n = \delta_{ref} = 0°$ the previously expression can be written as:

$$P_i = \sum_{j-1}^{n-1} B_{ij} \times \delta j \tag{4}$$

The DC power flow model in matrix form can be written by the following expressions:

$$\left[P\right] = \left[B\right] \times \left[\delta\right] \tag{5}$$

$$\left[\delta\right] = \left[B\right]^{-1} \times \left[P\right] \tag{6}$$

From expression (5) it can be derived that the power flow through the line $i-j$:

$$P_{i-j} = \frac{\delta_i - \delta_j}{jx_{i-j}} \tag{7}$$

where: x_{i-j} is reactance of the line $i-j$. The change of active power injection at bus k, shown by the expression:

$$P_k^{'} = P_k + \Delta P_k \tag{8}$$

leads to a change in all voltage angles $\left(\delta_1, \delta_2, ..., \delta_n\right)$ and consequently in power flows through all lines.

In this case, the change in power flow through the line $i-j$ is:

$$P_{i-j}^{'} = P_{i-j} + \Delta P_{i-j} = \frac{\delta_i^{'} - \delta_j^{'}}{jx_{i-j}} = \\ = \frac{\left(\delta_i + \Delta\delta_i\right) - \left(\delta_j + \Delta\delta_j\right)}{jx_{i-j}} \tag{9}$$

The change of existing, or adding new active power injection at bus k, can be written in the matrix form as follows:

$$\begin{bmatrix} \delta_1 \\ \delta_2 \\ \vdots \\ \delta_i \\ \vdots \\ \delta_j \\ \vdots \\ \delta_k \\ \vdots \\ \delta_{n-1} \end{bmatrix} = \begin{bmatrix} B_{11} & B_{12} & \cdots & B_{1i} & \cdots & B_{1j} & \cdots & B_{1k} & \cdots & B_{1n} \\ B_{21} & B_{22} & \cdots & B_{2i} & \cdots & B_{2j} & \cdots & B_{2k} & \cdots & B_{2n} \\ \vdots & \vdots & \ddots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \vdots \\ B_{i1} & B_{i2} & \cdots & B_{ii} & \cdots & B_{ij} & \cdots & B_{ik} & \cdots & B_{in} \\ \vdots & \cdots & \cdots & \cdots & \ddots & \cdots & \cdots & \cdots & \cdots & \vdots \\ B_{j1} & B_{j2} & \cdots & B_{ji} & \cdots & B_{jj} & \cdots & B_{jk} & \cdots & B_{jn} \\ \vdots & \cdots & \cdots & \cdots & \cdots & \cdots & \ddots & \cdots & \cdots & \vdots \\ B_{k1} & B_{k2} & \cdots & B_{ki} & \cdots & B_{kj} & \cdots & B_{kk} & \cdots & B_{kn} \\ \vdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \ddots & \vdots \\ B_{n1} & B_{n2} & \cdots & B_{ni} & \cdots & B_{nj} & \cdots & B_{nk} & \cdots & B_{nn} \end{bmatrix}^{-1} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_i \\ \vdots \\ P_j \\ \vdots \\ P_k \\ \vdots \\ P_{n-1} \end{bmatrix} \tag{10}$$

Once P_k is added, expression (6) can be written as follows:

$$\begin{bmatrix} \delta_1 + \Delta\delta_1 \\ \delta_2 + \Delta\delta_2 \\ \vdots \\ \delta_i + \Delta\delta_i \\ \vdots \\ \delta_j + \Delta\delta_j \\ \vdots \\ \delta_k + \Delta\delta_k \\ \vdots \end{bmatrix} = \left[B\right]^{-1} \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_i \\ \vdots \\ P_j \\ \vdots \\ P_k + \Delta P_k \\ \vdots \end{bmatrix} \tag{11}$$

To determine the impact of new generation unit to the existing (or new) network elements, loading of that element needs to be compared before and after the connection of new source to the network. For that reason, coefficient μ is introduced:

$$\frac{\Delta P_{i-j}}{\Delta P_k} = \mu_{i-j} \tag{12}$$

The μ coefficient shows the trend of load flow on a particular network element depending on the (additional) injection of power into a particular node. This means that load flow calculations are firstly performed for base model N state and then compared with the load flow calculations for each of the scenarios performed [12]. For example, if there is an injection of new generation to the system, load flow calculations are performed for that injection and its influence is observed with regard to the change in generation of the model, i.e. the new injection. This way influence of this injection (changes) on the grid elements can be monitored and evaluated. The higher the μ coefficient is, the greater the influence this injection has on the element (s). This is done for each coinciding element and thus creating the matrix. Non-coinciding (diagonal) elements have the value of 0 (hollow matrix or zero-diagonal matrix).

By expanding the matrix $[\mu]$ in corelation with model year r according to the schedule by adding scheduling discrete steps, 3D matrix is formed:

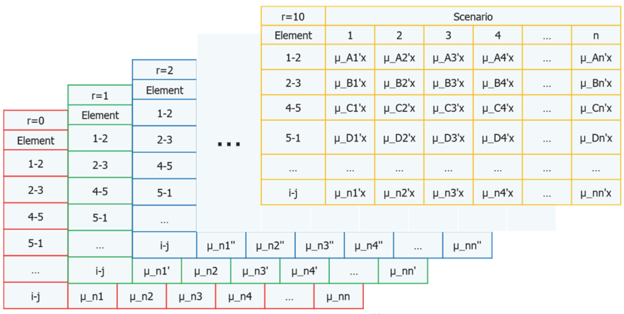

Figure 1 Three-dimensional coefficient $[\mu]$ matrix

4 CASE STUDY
4.1 Simple Test System Description

To show the applicability and efficiency of the proposed method, it is applied on the 5-bus test network, shown in the Figure 2 (modified IEEE 5-bus test network - branch 2 - 4 has been removed to better see the effects of the research). In this network there are 2 generators connected directly to the buses 1 and 2 providing the necessary power to meet the system's demand. The generator connected to the bus 1 is set the slack bus. The IEEE test networks are widely (and mainly) used for power flow analyses. They are also used to analyse the stability of the power system under different operating conditions and disturbances. Lately, these networks are used for optimization studies. It is widely used for educational purposes to teach students about power system operation, control and stability.

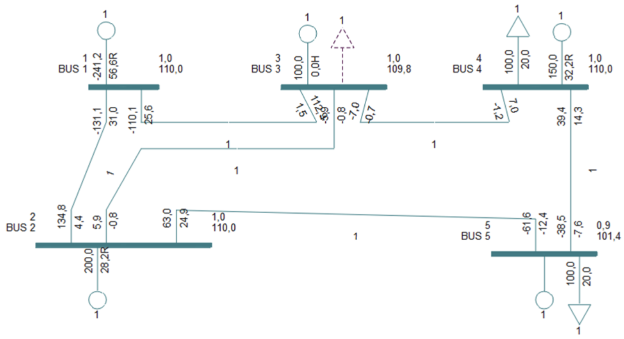

Figure 2 Test network prepared in Siemens PTI PSS/E [16]

Basic data on generation and consumption as well as parameters of lines and transformers are taken from the literature [11-14]. Some experiences on European level are considered from [15].

This (modified) test network has been used to test the hypothesis: load flow results in correlation with change of injection can be described by a number without unit of measurement (coefficient) to observe the trendline. The higher this number is, the greater the chance that the observed element (s) will reach its limits. If there is a way to compare it to another coefficient, some conclusions can be drawn. If that other number is percentage of loading of an observed element, together these 2 numbers can give adequately precise description of the system status and, potentially, foresee the future system need in an optimal manner.

To show the impact of new generation to the grid, several analyses have been made. Steady state DC load flow was observed with regard to the new generation in the system and by comparing it to the original model, thus creating the matrix shown in table 1.

S1, S2 and S3 represent scenarios with different generation increase in the model. S1 represent new generation in bus 2, S2 represent new generation in bus 4 and S3 represent new generation in buses 2 and 4 at the same time.

Table 1 Simulation results on 5-bus test network

	S1		S2		S3	
branch	μ	loading	μ	loading	μ	loading
1 - 2	0,4	0,70	0,35	0,65	0,24	0,76
1 - 3	0,2	0,85	0,14	0,80	0,57	1,17
2 - 3	0,2	0,61	0,05	0,48	0,28	0,68
2 - 5	0,03	0,57	0,07	0,60	0,02	0,52
3 - 4	0,14	0,74	0,16	0,76	0,39	0,96
4 - 5	0,03	0,67	0,23	0,84	0,31	0,91

2 things can be seen: the higher the μ coefficient is, it is showing that there is increase in the loading percentage. But it can also be misleading only to base these decisions on the μ itself but rather look at the loading. It can be seen for scenario S3 on the branch 1 - 3 that the μ is high and the loading is over 100%.

There is a causality between the element loading and μ coefficient, it just needs to be investigated further but, again, overseen by human eyes in order to evaluate the right causality and correlation.

In order to expand these hypotheses and to better understand the relationship between these parameters, more complex analyses have been conducted. Model used for simulations is that of PSS/E example library - SAVNW

[16]. The model itself can be seen in figure 4. It has 3 subsystems connected with many branches, different voltage levels and, generally, a well-balanced test environment.

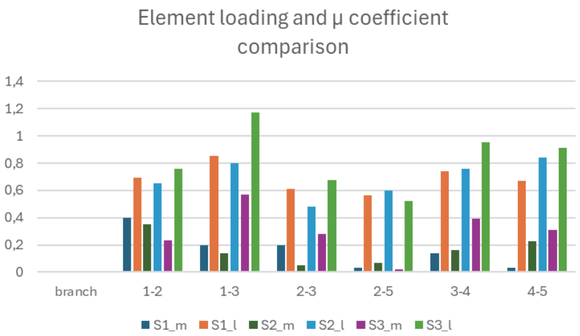

Figure 3 Graph representation of the data in table 2

4.2 Simulation Results

To prepare for calculations, defining the model is the first step, i.e. defining the network data that consists of bus data and line data, then creating admittance matrix, preparing load flow equations, solving the linear equations and, finally, calculating power flows. All buses with their respective voltage levels, types (slack, PV or PQ), and initial settings for voltage magnitudes and angles need to be listed. Impedance (resistance and reactance) of the transmission lines connecting the buses need to be specified along with susceptance.

Once all data is known, next step is formulating the admittance matrix (Y-Bus). Calculating the admittance of each line and forming the Y-bus matrix. For a DC load flow, only the real part (conductance) is considered. Using the DC load flow approximation assumes that voltage angles are small and voltage magnitudes are close to 1.0 per unit. This simplifies the power flow equations to linear equations. Using methods like Gaussian elimination or matrix inversion to solve the linear equations for the voltage angles at each bus. Once the bus voltages are known, power flows on each line using the solved voltage angles and the line admittances are calculated.

Planning problem was described earlier in the article. Assuming that in this test network there are 2 new requests to connect to the grid, means 2 new (different) generation units.

One unit will connect to the bus 152 and the other to the bus 154. Requested connection capacities are 100 MW and 200 MW. They can be numerated Gn1 and Gn2, respectively. Additionally, these new generation units will not connect to the grid at the same time. In the following table these requests can be seen:

Table 2 New generation entering the test system

Name	Capacity / MW	Point of connection	Commissioning year*
Gn1	100	Bus 152	2027
Gn2	200	Bus 154	2026

*These simulations are done based on the current year being 2024 and with no increase in the load of the system.

Analyses of the original grid in normal, steady state load flow calculations show that the grid is secure. Once an N-1 contingency analysis is conducted, it can be seen that the grid shows no overloaded elements.

Once the suggested new injections to the test grid are added, changes in the loading of the network elements can be seen. Those elements that had higher loading in the original N and N-1 load flow calculations are almost certain candidates (elements) to be overloaded with the added generation. Obviously, there is a great dependency and causal relationship between the bus of the new injection (added MWs) and the element that had higher loading in the original network. This can be seen in the figure 4.

Development of the projects waiting to be connected to the grid and the grid development itself are not strictly related in terms of time and space. There is a discrepancy in the time needed to develop grid and to develop (RES) projects. Because of this, system operators and developers are facing a spatial problem but also a temporal problem where developers are thinking in discrete steps of one year and system operators are (mainly) focused on ten-year periods with focus being on 3-year investment periods. In 3 years, developers can reach more advanced project stages, presumably even Ready To Build (RTB) stage of the project(s), depending on the size and the preferred location of the project (connection).

Development and construction of the grid elements (lines and substations) follows a similar path as development of new RES (New RES being solar and wind power plants). In 3 years (most) system operators, especially transmission system operators, cannot achieve the same milestones as developers.

For that reason, equilibrium needs to be found between expectations of the RES development and reality of the system development. Calculations in the following study case (and scenarios) have been made using DC load flow (DCLF) methodology

When n-1 contingency is analysed for the base model, it can be observed that the main issue(s) occurs at the bus 153. Out of 5 events, 4 occur at the bus 153. It can be observed that already 2 lines (branches) exist between buses 153 and 154.

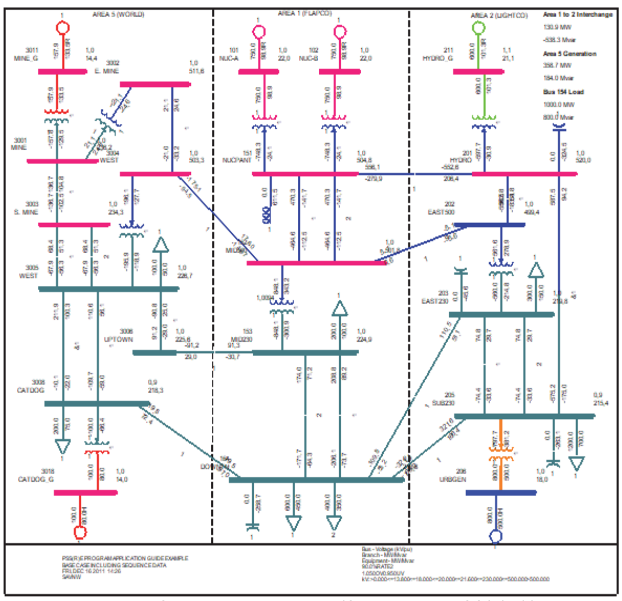

Figure 4 SAVNW example case (Siemens PTI PSS/E) [16]

Table 3 Overloaded elements in base model

From	To	Rating	MW	%
153	154	300	330,6	110,2
153	154	300	330,8	110,3
153	154	300	366,8	122,3
153	154	300	315	105,0
154	203	250	305	122,0

By analysing this data, all of the outages that have the negative effect on the bus 153 (and 154) happen when the affected branch is directly connected to bus 153 (or 154) or the neighbouring bus - which is to be expected. Change the transformer setting from mode 0 to mode 3 ("monitor MW"), meaning that this transformer has become a phase-shifting transformer (PST), from bus 206 to bus 205 did not help in resolving the issue(s).

Several cases (scenarios) will be observed to closely monitor and better understand what is happening with the system. Some examples and guidelines on defining scenarios came from personal experience and from [17].

Scenario 1: When new line 153 - 154 (3) is in operation, only overloaded element is:

Table 4 Overloaded elements in scenario 1 model

From	To	Rating	MW	%
154	203	250,0	−283,0	113,2

When new line 154 - 203 is in operation, there are no overloaded elements and the contingency analysis is complete for the base case scenario. Now the spatial-temporal increment in generation can be observed. So, to conclude, there were 5 events with overloaded elements in PSS/E ACCC contingency analysis. PSS/E (Power System Simulator for Engineering) is a software tool used for the analysis and planning of electrical power systems created by Siemens PTI. One of its features is ACCC (AC Contingency Calculation), which is used for contingency analysis in power systems. ACCC helps in evaluating the impact of potential outages or failures (contingencies) in the power system. It automatically simulates various scenarios where different components (like transmission lines or transformers) are taken out of service one at a time. This helps in understanding how the system will behave under different failure conditions and ensures that the system can continue to operate reliably. While researching this topic on contingency analysis, authors consulted previous work done by.

The process involves using several files:

- Contingency file (.con) - specifies which components to take out of service.
- Monitor file (.mon) - indicates which system elements to monitor during the contingencies.
- Subsystem file (.sub) - defines the parts of the system to be analyzed.
- By using these files, ACCC can generate reports that highlight potential overloads and voltage issues, helping engineers to plan and reinforce the power system accordingly.

By adding 2 new elements (lines), there were no such elements and base case scenario contingency analysis is done.

As described earlier, first (new) power plant will get into operation in 2 years. That is not enough time for the system operator to construct the necessary lines in order for them to be able to help the system with the intake of new generation. New 100 MW to connect the existing bus 152. Four cases will be analysed: without proposed grid reinforcements (Scenario 2a), with included (already built) 2 new lines, firstly each of the lines 153 - 154 (Scenario 2b1) and 154 - 203 (Scenario 2b2) and both of them in operation (Scenario 2b3). These items in the following tables represent events, i.e. overloaded elements (lines) that occurred as a result of another element outage.

For scenario 2a - no grid reinforcements, new generation in bus 152. In over ten cases, loading of the elements was very close to 100% which is very indicative (such cases are not shown in the table below).

Table 5 Overloaded elements in scenario 2a model

From	To	Rating	MW	%
153	154	300	338,1	112,7
153	154	300	337,8	112,6
153	154	300	374,8	124,9
153	154	300	323,1	107,7
154	203	200	−308,8	154,4

For scenario 2b1 - only line 153 - 154(3) in operation, new generation in bus 152:

Table 6 Overloaded elements in scenario 2b1 model

From	To	Rating	MW	%
154	203	200	−283	141,5

For scenario 2b2 - only line 154 - 203(2) in operation, new generation in bus 152:

Table 7 Overloaded elements in scenario 2b2 model

From	To	Rating	MW	%
153	154	300	337,8	112,6
153	154	300	336,7	112,2
153	154	300	373,5	124,5
153	154	300	305,3	101,8

For scenario 2b3 - both lines in operation, new generation in bus 152:

Table 8 Overloaded elements in scenario 2b3 model

From	To	Rating	MW	%
153	154	300	302,1	100,7
153	154	300	302,4	100,8

Since this is a mathematical operation involving rounding up of the grid elements parameters (R, X, B), and inaccuracies in the calculation procedures itself (or by using different calculation methods - Full, Decoupled or Fixed-slope Newton-Raphson), without impacting the results, data analyses and conclusions, it is safe to disregard any overloads below 5%, meaning that only elements that have loading higher than 105% can be observed regarding any further conclusions. There are only few such elements in the analyses above and for scenario 2b3 where above mentioned grid reinforcements have been implemented, it is safe to conclude that with reinforcements in place, there are no overloaded elements. As can be seem from scenario 2b3, there is no (negative) impact on contingency analysis. This means that the proposed solution of introducing two new lines to the system is optimal.

Moving to scenario 3 - adding 200 MW to bus 154. As previous, multiple variants will be analysed - with and without grid reinforcements but also with and without new generation in bus 152. Meaning there are 7 (sub)variants of scenario 3:

Scenario 3a - no grid reinforcements, generation at bus 152, generation at bus 154.

Table 9 Overloaded elements in scenario 3a model

From	To	Rating	MW	%
153	154	300	314,6	104,9
154	203	200	−285	142,5

Scenario 3b1 - only line 153 - 154(3) in operation, generation at bus 152, generation at bus 154

Table 10 Overloaded elements in scenario 3b1 model

From	To	Rating	MW	%
154	203	200	−264,1	132,1

Scenario 3b2 - only line 153-154(3) in operation, no generation at bus 152, generation at bus 154

Table 11 Overloaded elements in scenario 3b2 model

From	To	Rating	MW	%
154	203	200	−260,5	130,3

Scenario 3c1 - only line 154-203(2) in operation, generation at bus 152, generation at bus 154

Table 12 Overloaded elements in scenario 3c1 model

From	To	Rating	MW	%
153	154	300	313,6	104,5

Scenario 3c2 - only line 154 - 203(2) in operation, no generation at bus 152, generation at bus 154

Table 13 Overloaded elements in scenario 3c2 model

From	To	Rating	MW	%
153	154	300	304,7	101,6

Scenario 3d1 - both lines in operation, generation at bus 152, generation at bus 154

Table 14 Overloaded elements in scenario 3d1 model

From	To	Rating	MW	%
204	205	800	811,9	101,5
153	154	300	330,1	110,0

Scenario 3d2 - both lines in operation, no generation at bus 152, generation at bus 154

Table 15 Overloaded elements in scenario 3d2 model

From	To	Rating	MW	%
204	205	800	870,9	108,9

With reinforcements in place, there are no overloaded elements.

Adding new generation to the bus 154 improved the situation in the grid and there is no need to construct new line.

Distribution of the coefficient μ for scenarios S0, S1, S2 and S3 is shown in Figure 5. It shows how new generation impacts existing (and new) grid elements/lines throughout abovementioned scenarios. The higher the "amplitude", i.e. the value, coefficient μ has, the greater the impact it has on the overall state of the grid itself. This means that high values show the sensitivity of that specific grid element to disturbances in the grid. It also can be a good indicator that this grid element is a prominent candidate for reaction. Either it is upgrading the capacity of existing element or adding new element (s) in parallel with the one observed.

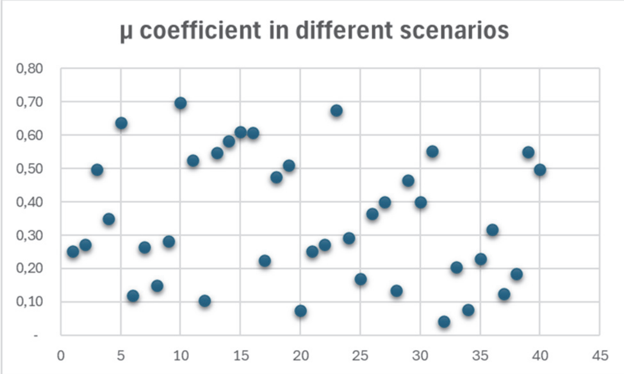

Figure 5 μ coefficient distribution with regard to scenario

4.3. Potential (General) Solutions

To reduce the loading below 100% on the lines where it is currently over 100%, several measures can be considered:

- Adding parallel lines between buses can help distribute the load more evenly and reduce the burden on the existing lines.
- Reconfiguring the network by changing the topology can help balance the load. This might involve:
    a. Creating new connections between buses that are not currently connected.
    b. Removing or rerouting existing lines to optimize the load distribution.
- Implementing load shedding on buses with high demand can reduce the overall load on the network. This involves temporarily disconnecting certain loads to prevent overloading.
- Redistributing the generation across different buses can help balance the load.
- Upgrading the capacity of existing lines can help them handle more load without exceeding their limits.
- Flexible AC Transmission Systems (FACTS) devices can help control power flows and improve the stability of the network.

Also, changing the topology of the grid by splitting one bus into two is a realistic temporary solution. This can help redistribute the load and potentially reduce overloading on certain lines. Firstly, identify the "best" bus to split: Best candidate is a bus with high load or generation that is contributing to overloading.

Selected bus needs to be split into two buses, each with a portion of the original load and generation. Adjustment of the connections is necessary so that the new buses are connected to the appropriate lines and other buses. In these examples, bus 2 has significant generation and load, and splitting it could help distribute the load more evenly. Also, bus 4 has high generation after adding additional MW and splitting it could reduce the load on the lines connected to it [18].

Splitting a bus will change the admittance matrix and the load flow calculations. The load and generation will be redistributed between the new buses, potentially reducing the load on the lines connected to the original bus. The new buses will need to be connected to the existing network, which will change the power flow paths and potentially reduce overloading on certain lines. Admittance matrix will need to be updated to reflect the new connections and the split bus [19].

4.4. Optimization Method(S)

As it can be seen in Fig. 5., coefficient μ is not an obvious or easy thing to understand. Finding solutions and implementing them is what is the next step in the research. One of the possible approaches is using Particle Swarm Optimization (PSO). This has several advantages. PSO is relatively simple to implement compared to other optimization algorithms. It does not require complex mathematical operations. It often quickly converges to an optimal solution, especially in the early stages of the search. Since the updates of particle positions and velocities can be performed independently, PSO is suitable for parallelization, which can significantly speed up the optimization process.

PSO is also robust and can be applied to a wide range of problems, including those with multiple dimensions and complex objective functions. The parameters can be adjusted to improve the algorithm's performance for specific problems. Good global search capability means it can avoid local minimums and find globally optimal solutions.

Pseudocode for PSO that could be applied to the problems described in this research is as follows:

for *each particle i=1,...,S* ***to***
Initialize the position of a particle with a uniformly distributed random vector: x_i~U(b_lo,b_up)
Initialize the best known position of the particle to the initial position: p_i←x_i
if 〖f(p〗 *_i)<f(g) then*
Update Best Known Swarm Position: Mr←p_i
Initialize particle velocity v_i ~ U(−|b_up−b_lo |,|b_up−b_lo |)
while until the criterion for exiting the loop is met
for each particle i=1,..., S to
for each dimension d=1,...,n
Choose random numbers: r_p 〖, r〗 *_g~ U(0, 1)*
Update particle velocity: v_(i,d)← 〖*ωv*〗 *_(i,d)+φ_pr_p (p_(i,d)-x_(i,d))+φ_gr_g (g_d-x_(i,d))*
Update Particle Position:x_i←x_i+lrv_i
if 〖*f(x*〗 *_i)<f(p_i) then*
Update Best Known Particle Position p_i←x_i
if f(p_i)<f(g) then
Update the best known swarm position 〖*g←p*〗 *_i*

This pseudocode describes the Particle Swarm Optimization (PSO) algorithm. It initializes a swarm of particles with random positions and velocities. Each particle updates its position and velocity based on its own best-known position and the best-known position of the swarm. The process continues iteratively until a stopping criterion is met, aiming to find the optimal solution to a given problem. Further research will define if the hypothesis was set correctly.

5 CONCLUSION

While going through the previous work and research done by others, mainly [20-22], but also based on the previous work done by the authors, this paper started to make its shape. The integration of renewable energy sources into the power grid presents both challenges and opportunities for grid planners. The variability and intermittency of renewable energy sources like wind and solar necessitate the development of flexible and responsive systems to balance supply and demand. Traditional power plants, which provide consistent and controllable power, have long been the backbone of grid stability. However, the increasing penetration of renewables introduces complexities such as voltage instability and frequency fluctuations. To address these issues, grid planners must implement advanced technologies and strategies, including energy storage systems and smart grid technologies, to maintain stability and reliability.

Significant upgrades to the existing grid infrastructure are required to accommodate the transition to renewable energy. This includes expanding transmission lines to connect remote renewable energy sites to the main grid and enhancing distribution networks to handle the increased load and variability. The shift towards a more decentralized energy system, where power generation occurs closer to consumption points, challenges traditional centralized grid models. Grid planners must now incorporate distributed energy resources (DERs) like rooftop solar panels and local wind turbines into their planning processes.

The transition to renewable energy also demands substantial investment in new technologies and infrastructure. Grid planners must navigate evolving policies and regulations aimed at promoting renewable energy adoption and ensuring grid resilience. As climate change exacerbates the frequency and severity of extreme weather events, grid planners must design systems resilient to these impacts. This includes hardening infrastructure against storms and heatwaves and incorporating climate risk assessments into planning processes.

Grid planners can create a more sustainable, reliable, and resilient energy system that effectively integrates renewable energy sources. The optimization of electricity network development is crucial to ensure that new power plants can connect seamlessly without compromising system safety and reliability. The planning and development of transmission systems are becoming increasingly complex, especially when there are no guarantees that all proposed power plants will ultimately be built and connected to the network.

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